

1 **VOLTAGE MODE, HIGH ACCURACY BATTERY CHARGER**
2

3 The present application claims priority to Provisional Application Serial
4 No. 60/313,260, filed August 17, 2001, and assigned to the same assignee.

5 **Field of the Invention**

6 The present invention relates to a battery charger circuit for charging one or more
7 batteries. In particular, the present invention relates to a voltage mode battery charger
8 that uses both current and voltage control to regulate the charging cycle and to provide
9 accurate charging and charge termination.

10 **Summary of the Invention**

11 In one aspect, the present invention provides a circuit for adjusting the duty cycle
12 of a PWM signal. The circuit includes a battery current control section that generates a
13 current control signal proportional to an amount battery charging current exceeds a
14 predetermined battery charging current threshold. The circuit also includes a battery
15 voltage control section that generates a voltage control signal proportional to an amount a
16 battery voltage exceeds a predetermined battery voltage threshold. A compensation
17 capacitor and a current source charging the compensation capacitor are also provided. A
18 comparator generates a PWM signal based on the amplitude of the voltage on the
19 compensation capacitor. The current source and the current control signal and voltage
20 control signal are summed together at a common node, so that the current control signal
21 and/or said voltage control signal reduce the voltage on the compensation capacitor
22 thereby reducing the duty cycle of the PWM signal.

23 In another aspect, the present invention provides a battery charging circuit that
24 includes a current control circuit generating a current control signal proportional to the

1 amount battery charging current exceeds a predetermined battery charging current
2 threshold; a voltage control circuit generating a voltage control signal to the amount
3 battery voltage exceeds a predetermined battery voltage threshold; a DC/DC converter
4 circuit generating the battery charging current from a DC source; and a PWM signal
5 generator circuit generating a PWM signal for controlling the duty cycle of the DC/DC
6 converter circuit. The PWM circuit comprises a comparator, an oscillator, a
7 compensation capacitor and a current source charging the compensation capacitor. The
8 comparator generates the PWM signal based on the voltage on the compensation
9 capacitor. The current source and the current control signal and voltage control signal are
10 summed together at a common node so that the current control signal and/or the voltage
11 control signal reduce the voltage on the compensation capacitor thereby reducing the duty
12 cycle of the PWM signal and thereby reducing the current delivered by the DC/DC
13 converter circuit.

14 It will be appreciated by those skilled in the art that although the following
15 Detailed Description will proceed with reference being made to preferred embodiments
16 and methods of use, the present invention is not intended to be limited to these preferred
17 embodiments and methods of use. Rather, the present invention is of broad scope and is
18 intended to be limited as only set forth in the accompanying claims.

19 Other features and advantages of the present invention will become apparent as
20 the following Detailed Description proceeds, and upon reference to the Drawings,
21 wherein like numerals depict like parts, and wherein:

1 Brief Description of the Drawings

2 Figure 1 is a block diagram of an exemplary battery cell charging system
3 according to the present invention;

4 Figure 2 is an exemplary amplifier circuit of the present invention; and

5 Figure 3 is a timing diagram representing an oscillator signal and DC signal to
6 generate a PWM signal of the system of Figure 1.

7 Detailed Description of Exemplary Embodiments

8 Figure 1 depicts a voltage mode battery charger system 10 according to one
9 exemplary embodiment. The system 10 includes a voltage mode battery charger circuit
10 12 for charging one or more batteries 16 using a DC source 14. The DC source may be
11 an AC/DC adapter or other power supply. Circuit 12 operates to control the duty cycle of
12 the Buck converter circuit 18 (comprising an inductor and capacitor, as is well
13 understood in the art) via switches 20, to control the amount of charging power delivered
14 to the battery 16. As an overview, circuit 12 controls the duty cycle of the Buck
15 converter 18 by monitoring the source current, the battery charging current (current
16 mode) and the battery voltage (voltage mode). Battery charging current is sensed across
17 the sense resistor (or impedance) R_{sch} . Instead of sensing the current through the
18 inductor (as in conventional current mode topologies), the present invention uses a
19 voltage mode topology by sensing the current across R_{sch} . In this manner, and by
20 utilizing both battery current control and voltage, the present invention achieves more
21 accurate charging of the battery towards the end of the charging cycle, and provides more
22 accurate charge termination than can be achieved with conventional current mode
23 charging topologies. The details of the system 10 are described below.

1 Essentially, the charger circuit 12 operates to control the duty cycle of the buck
2 converter 18 by controlling the power on the compensation capacitor Ccomp 38. The
3 circuit 12 includes a battery current control section comprised of sense amplifier 26 and
4 transconductance amplifier 28, a battery voltage control section comprised of summing
5 block 30 and transconductance amplifier 32, and a power control section comprised of
6 sense amplifier 34 and transconductance amplifier 36. The battery current control section
7 and battery voltage control section each generate signals indicative of the battery current
8 and voltage, respectively. The power control section generates a signal indicative of the
9 power available from the source 14. Each of these sections is combined (at node 60), and
10 if any of these sections exceeds a threshold, the power delivered to the charge capacitor
11 decreases, thereby reducing the duty cycle of the Buck converter. This operation is
12 described in greater detail below.

13 The duty cycle of the Buck converter 18 is controlled by the comparator 40, via
14 switches 20. The input of the comparator 40 is the voltage on the compensation capacitor
15 (Ccomp) 38 and a sawtooth signal generated by the oscillator 44. The output of the
16 comparator 40 is a PWM signal 68, whose pulse width (duty cycle) is reflected in the
17 intersection of the amplitude of the voltage on Ccomp 38 and the sawtooth signal. In this
18 sense, the duty cycle of the PWM signal thus generated is based on the voltage on the
19 compensation capacitor 38 and the sawtooth signal generated by the oscillator 44.
20 “Based on”, as used herein, is to be interpreted broadly and generally means “as function
21 of” or “related to”. The higher the amplitude of the voltage on Ccomp, the greater the
22 duty cycle of the PWM signal 68. In the exemplary embodiment, the sawtooth signal is a
23 fixed frequency signal, and the duty cycle of the PWM is therefore adjusted by adjusting

1 the amplitude of the voltage on Ccomp 38. Ccomp 38 is charged by the current source
2 42. When no signal is generated by any of the current control section, the voltage control
3 section or the power control section, the current source charges Ccomp to maximum
4 level, and thus the PWM is at maximum duty cycle and the Buck converter is delivering
5 maximum charging current and voltage to the battery. Any signal generated by the
6 current control section, the voltage control section or the power control section acts as a
7 sink to the compensation capacitor 38, thereby reducing the voltage on the compensation
8 capacitor and thereby reducing the duty cycle of the PWM signal. In this manner,
9 charging current is controllably delivered to the battery 16. The particulars of the Buck
10 converter 18 and switches 20 are well understood in this art, and are not important to the
11 present invention, and may be generalized as a controllable DC/DC converter circuit.

12 Current Control

13 The current control section (circuit) includes a sense amplifier 26 and a
14 transconductance amplifier 28. The sense amplifier monitors the battery charging current
15 across the sense impedance Rsch 24, and generates a signal proportional to battery charge
16 current. The transconductance amplifier 28 receives the output of the sense amplifier 26
17 and compares that signal with a programmed (desired) battery current signal Ich. As a
18 general matter, the inputs of the transconductance amplifier 28 are voltage signals, and
19 the output is a proportional current signal. The output of the transconductance amplifier
20 is the current control signal 62, which is proportional to the amount the battery charging
21 current exceeds the programmed Ich. Ich is zero until the battery charging current
22 exceeds the programmed current value Ich. The programmed value Ich is set to

1 according to the particular battery type and requirements, for example set to charge a
2 conventional LiIon battery, as is well understood in the art.

3 If the battery charging current exceeds the threshold I_{ch} , the amplifier 28
4 generates a proportional current control signal 62. Since the output of the amplifier is
5 coupled to the negative side of the current source 42 (at node 60), any signal generated by
6 the amplifier 28 acts to sink current from the source 42. In turn, this operates to reduce
7 the voltage on Ccomp 38, thereby reducing the duty cycle of the PWM signal 68 and
8 reducing the charging current delivered to the battery. Since the output current control
9 signal 62 is proportional to the input values, the duty cycle is dynamically adjusted as a
10 function of battery charging current.

11 The current sense amplifier 26 may be a custom or off-the-shelf amplifier, as is
12 readily available in the art. However, as is also understood in the art, amplifier 26 must
13 provide large common mode voltage rejection. Accordingly, and referring now to Figure
14 2, another aspect of the present invention is an amplifier configuration to alleviate the
15 requirement for large common mode voltage rejection. The sense amplifier 26 depicted
16 in Figure 2 includes a switch 48 controlled by an operational amplifier 46, and gain
17 resistors R1 50 and R2 52. The amplifier 26 of Figure 2 is not sensitive to common mode
18 voltage. Rather, the switch transfers the floating differential voltage that appears across
19 R_{sch} by referring it to ground and amplifying the voltage according to the gain given by
20 $R2/R1$.

21 Voltage Control

22 The voltage control section (circuit) includes the summing block 30 and a
23 transconductance amplifier 32. In the exemplary embodiment, the summing block 30

1 includes three inputs: a high-precision reference or trim voltage Ref, a voltage set (Vset)
2 and a voltage correction (Vcor) signal. In the exemplary embodiment, the battery 16 is a
3 LiIon battery. LiIon batteries are very sensitive to overvoltage conditions, and indeed
4 become hazardous if overcharged. Thus, the reference or trim signal Ref is accurate to
5 within the tolerance required by the battery. For LiIon, the tolerance is on the order of
6 +/- 0.005 Volts. However, other battery types and reference voltage requirements are
7 equally contemplated herein. Vset represents a voltage setting value, usually supplied by
8 the manufacturer of the battery. Vcor is a correction signal that is proportional to the
9 charging current, and is provided as a compensation signal for the particulars of the
10 charging apparatus and for parasitic resistance associated with the battery (since battery
11 voltage cannot be measured directly, and one must factor in parasitic resistance).
12 Although not shown, Vcor can be obtained by tapping a voltage divider placed in parallel
13 with the output of sense amplifier 26. These three signals are summed in a weighted
14 fashion in summing block 30. For example, the output of the summing block 30 can be
15 set to the reference voltage + (Vset/x) + Vcor/y; where x and y are chosen in accordance
16 with the desired voltage setting value and correction value, respectively. Vcor and Vset
17 need not be as accurate as the reference voltage, since their contribution is divided
18 diminished by x and y.

19 The output weighted voltage signal from the summer block 30 may be generally
20 deemed as a predetermined battery voltage threshold signal. The transconductance
21 amplifier 32 compares the output of the summer block to the battery voltage. The output
22 of the amplifier 32 is a voltage control signal 64, which is proportional to the amount the
23 battery voltage exceeds the threshold established by the summing block. As with the

current control section described above, signal 64 is nonzero if the battery voltage exceeds the threshold determined by the summer block. Since the output of the amplifier 32 is coupled to the negative side of the current source 42 (at node 60), any signal 64 generated by the amplifier 32 acts to sink current from the source. In turn, this operates to reduce the voltage on Ccomp 38, thereby reducing the duty cycle of the PWM signal 68 and reducing the charging current delivered to the battery. Since the output 64 of the amplifier 32 is proportional to the input values, the duty cycle is dynamically adjusted to achieve a desired battery voltage.

Power Control

The power control section (circuit) includes a sense amplifier 34 and a transconductance amplifier 36. The power control section is provided to reduce the duty cycle of the Buck converter, and thereby reduce the charging current delivered to the battery if the DC source needs to deliver more power to an active system 72 (e.g., portable electronic device) attached to the source. The active system is coupled in parallel to the charging system 10 across the sense resistor Rsac. Since the total amount of power provided by the source 14 is fixed, in a well-designed system the load requirements of the active system and battery charging circuit are balanced. The power control section ensures that the active system always takes priority (in terms of power requirements) by reducing the charging current to meet the demands of the active system. Accordingly, the power control section generates a power control signal 66 proportional to the amount of power required by the battery charger and the active system exceeds the threshold I_{ac_lim} . I_{ac_lim} is typically the maximum that can be delivered by the adapter source 14. For example, the source 14 may be simultaneously supplying power to an

1 active system (not shown) and charging current to the battery. If the portable system
2 requires more power, charging current to the battery is accordingly reduced to meet the
3 demands of the system. The source 14 is generally defined as a DC power source, as
4 may be supplied from an AC/DC adapter.

5 The sense amplifier 34 monitors the total adapter current delivered by the source
6 14 across the sense impedance R_{sac} 22. The total adapter (source) current includes the
7 system current (i.e., current delivered to a portable system (not shown) connected to the
8 source 14) and the battery charger circuit 12 (which is a measure of the charging current
9 divided by duty cycle of the Buck converter 18). The signal across the sense resistor
10 R_{sac} is a signal proportional to the total adapter current. The transconductance amplifier
11 36 receives the output of the sense amplifier 34 and compares that signal with a power
12 threshold signal I_{ac_lim} . Thus, if the signal across the sense resistor is larger than
13 I_{ac_lim} , this indicates that the system is requiring more power, and accordingly battery
14 charging current is to be reduced. Of course, this limit signal may be fixed, or may be
15 adjusted based on the dynamic power requirements of the system and/or changes in the
16 source. The output of the transconductance amplifier is the power control signal 66,
17 which is zero until the power required by the battery charger and the active system
18 exceeds the threshold value I_{ac_lim} .

19 If the power required by the battery charger and the active system exceeds the
20 threshold I_{ac_lim} , the amplifier 36 generates a proportional power control signal 66.
21 Since the output of the amplifier is coupled to the negative side of the current source 42
22 (at node 60), any signal generated by the amplifier 36 acts to sink current from the
23 source. In turn, this operates to reduce the voltage on C_{comp} 38, thereby reducing the

1 duty cycle of the PWM signal 68 and reducing the charging current delivered to the
2 battery. Since the output 66 of the amplifier 36 is proportional to the input values, the
3 duty cycle is dynamically adjusted as a function of balancing power demands between a
4 system and the battery, and so as not to exceed a maximum power output of the DC
5 source 14.

6 Figure 3 depicts a timing diagram 70 representing the PWM signal 68 (bottom
7 figure) and the intersection between the voltage on the compensation capacitor, V_{comp} ,
8 and the sawtooth signal 44 (top figure). In the present exemplary embodiment, V_{comp}
9 is essentially a DC signal whose amplitude is moved up by the current source 42, and
10 down by either the current control signal 62, the voltage control signal 64 or the power
11 control signal 66. In other words, the value (amplitude) of V_{comp} is the sum of signals
12 $(42 - (62, 64 \text{ and/or } 66))$. By moving the value of V_{comp} downward, the duty cycle of
13 PWM signal is decreased.

14 Thus, with present invention, the duty cycle of the PWM signal can be adjusted
15 using a differential the compensation capacitor. In the exemplary embodiments,
16 adjusting the PWM is accomplished dynamically as a function of battery charging
17 current, battery voltage and/or system power requirements. The topology depicted in
18 Figure 1 is a voltage mode topology. Voltage mode topology means that the sense
19 resistor R_{sch} is placed outside of the Buck converter, and thus the current across this
20 resistor is a DC value (without ripple). Those skilled in the art will recognize numerous
21 modifications to the present invention. These and all other modifications as may be
22 apparent to one skilled in the art are deemed within the spirit and scope of the present
23 invention, only as limited by the appended claims.